Development and Performance Verification of Pointing Control Systems of Optical Devices for Space Flight Missions

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論文内容要旨

Telescopes are powerful methods to observe other astral bodies. The observations find out unknown phenomena and give us new knowledge. However the seeings of a telescope, the qualities of observations, are easily affected by the actuation of the atmosphere and the weather conditions. In addition the observable bands of the wavelength of the light from stars are limited because of atmospheric absorptions.

A balloon borne telescope (BBT) is one of solutions against such limitations. A telescope is carried by a stratospheric balloon(an example is shown in Fig.1) to the stratosphere where is above the ozone layer and the atmospheric density is as one a hundredth thin as the sea level. The thin atmosphere occurs little seeing disturbances. Furthermore the environment enables observations of lights which cannot be observed on the ground. Such good atmospheric conditions allow telescopes to prepare as high resolution image as the diffraction limits.

One of the key technologies to take fine images with the balloon borne telescope is 'pointing control.' The pointing control systems and its devices are the main issues of this dissertation.

The environment in the stratosphere is much better for telescopic observations than on the ground. But a telescope with loose pointing control system cannot achieve images with good resolution even however good the environment is. The pointing control system must fix a target star in the observation field of view (FOV) during the exposure of the camera. The BBT we developed (Shown in Fig.2) was applied the adaptive optics with a tip-tile mirror(TTM), which controlled the location of the star image in the FOV by moving a mirror plate in the optical system.

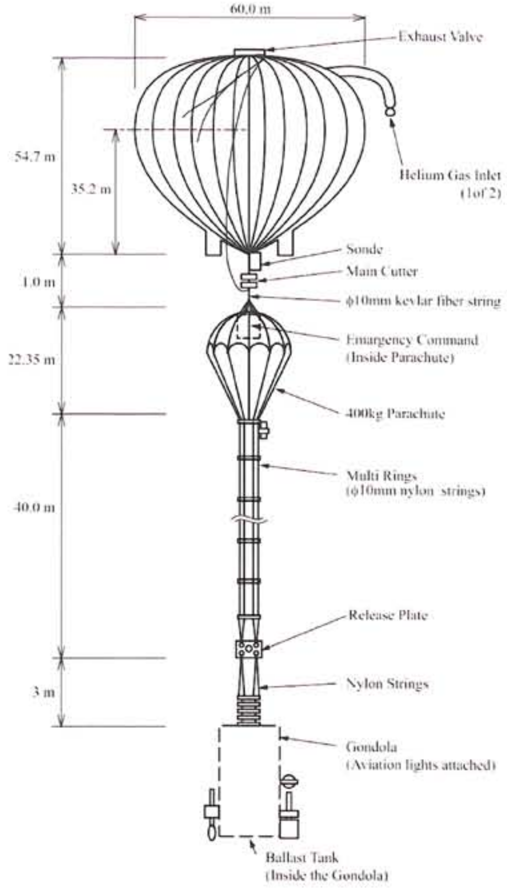

Fig.1. Balloon System

Fig.2. Gondola

The methods for fine imaging are effective only when the target star is caught in the FOV of the telescope. Ground telescopes easily introduce a target into the FOV because they are placed solid base and relative directions between the line of the sight of the telescope and the target are strictly determined. Contrastingly, a gondola hanged by a balloon is regarded as an unstable base of a telescope whose attitude is easily moved by disturbances. The problem of the introduction of the target into the FOV should be addressed with the stabilization of the attitude of the gondola.

Another interest of this dissertation is an evaluation of an alternate fine pointing actuator. As a technical matter, the TTM shifts its mirror with piezo actuators. As is known well, the actuator generates strain proportional to loaded voltage. The voltage usually rises up to tens of volts. In some cases it gets higher than a hundred volts. Such high voltages cause undesirable discharges when they are installed in the spacecraft and used in vacuum environment. In order to avoid them, therefore, a pointing system with a piezo actuated mirror is usually stored in an airtight case which maintains the air pressure around the actuator one atmosphere.

One solution is an application of current driven mirrors. Some of such mirrors have already been applied to telescopes on spacecrafts. But due to the relatively large mass or weak torque generation, they have been effective only in low frequency range. Recently a very lightweight, high response mirror has been developed with the micro-electric mechanical system (MEMS) technology. Evaluating the new technology and seeking out their application candidates are interesting issues.

This research is closely-correlated to the development of the BBT. The purposes of this dissertation are 1) to elaborate a 6ight system of a balloon borne telescope, 2) to verify a fine pointing control system, 3) to verify a candidate of a alternate fine pointing actuator, 4) to estimate possibilities of fine pointing applications for future spacecrafts.

First of all, two past examples of BBTs are reviewed. From the examples these important suggestions are drawn:

- Multiple control stages are appropriate to achieve precise pointing capability on a gondola.
- The key items of a fine pointing on a balloon gondola are ranges of the sensors and the actuators, moment of inertia of the controlled objects, and the control frequencies.
- A finer attitude sensor should cover properly the range of 6uctuation which is smaller than capability of coarser system.
- A controlled object should be set proper goal of the accuracy depending on the moment of inertia.
- Operation frequency of each stage should be determined with consideration of that
- of the disturbance which should be canceled in the stage.

Based on these suggestions, the policy of the pointing system of the new balloon borne telescope is determined as follows:

- The pointing control system consists of three stages: the gondola attitude control, the coarse pointing control of the telescope, and the fine pointing control with a tip-tilt precision mirror.
- The gondola attitude control system provides a solid base to the telescope.
- In order to cancel the attitude disturbance on the gondola, the telescope should be operated at a frequency higher than several hertz.
- The operation frequency of the fine pointing control should be as high as possible.

Along to the policies, the 6ight system of the balloon borne telescope was developed which included three stage pointing control system. Also the result of the 6ight operation is reported.

The performances of the pointing control system were verified in the series of the ground tests. The performance tests were divided into two stages. One is the performance test of the integration of the gondola attitude control and the coarse pointing control of the telescope. This test was conducted with the 6ight gondola hanged by the ceiling of a laboratory with a rope in order to verify the performance under near 6ight environment. Another is the verification of the integration of the coarse pointing control and the fine pointing control. This test was conducted with a real planet and the accuracy of the control was measured.

Due to the limitation of the experiment environment, the total integration of the three pointing controls could not be conducted. Therefore the total performance was estimated based on the two ground tests. The discussion pointed out that the target star would go out of the effective area of the TTM due to the discontinuity from the magnitude of the tracking error of the coarse pointing control to the compensative area of the fine pointing control. On the other hand, the precision in this B09-03 6ight operation was estimated acceptable because the duration to keep the target at the center of the FOV was estimated enough compared with the exposure time of the camera.

The existing TTM performed effectively in the BBT observation system. It suppressed well the tracking error of the coarse pointing control. The effective frequency range up to 50Hz, which is the dynamic resonant frequency of the mirror, is higher than ever taken by telescopes on spacecrafts. Usually spacecrafts stabilize their attitude with spinning wheels. The vibration generated due to the unbalance of wheel often affects the observation performance. Therefore, future TTM will be required the capability of vibration suppression in higher frequency range.

A MEMS mirror was investigated as one of the candidates of the fine pointing actuator for future telescope. It has a two-axial gimbal and generates the operation torque with electric current on coils. The coils are manufactured on the narrow gimbal and the back of the mirror by the MEMS technology.

The commercial MEMS mirrors are designed as a laser scanner, to drive the mirror vibrated at the structural resonant frequency and to obtain large amplitude. However the application assumed in this research is 'DC drive' which drives the mirror at any frequency with small amplitude. Therefore, first of all, the test piece was introduced and the principle of the drive was explained. Also a prototype model of the feedback controller for DC drive of the mirror was developed. As the performance evaluation the frequency characteristics of the mirror under the open loop control and the closed loop control were measured and evaluated. The mirror under the open loop control behaved as a viscous damping system with a small damping coefficient. The frequency characteristics under the closed loop control showed the equivalent performance with the existing TTM.

The demands for the pointing control technologies of spacecrafts are growing with each passing year. This dissertation will be helpful for future developments of spacecrafts for optical observations.

論文審査結果の要旨

大気の薄い成層圏高度より天体を観測する高層気球望遠鏡は，大型の地上望遠鏡や打ち上げ機会が限られる望遠鏡衛星に比べて有用性の高い天文観測手段として注目を集めている。1960 年代には米国にて大型の気球望遠鏡が開発されたが，実用性に欠けるものであった。日本では 1970 年代後半より，宇宙科学研究所にて 500kg 級の高層気球実験が行われてきており，気球搭載望遠鏡も開発されているが，対象天体を捉えるためのポインティング制御についは，改良の余地が多く残されている。本論文は，高層気球望遠鏡において 0.1 秒角の精度にせまるポインティング制御を実現するためのシステム設計，制御系開発，地上実験およびフライト実験をおこなった成果をまとめたものであり，全編 6 章より構成される。

第 1 章は序論であり，本研究の背景と目的について述べている。

第 2 章では，開発された気球望遠鏡システムの基本構成，および北海道大樹町にて実施されたフライト実験の概要について述べられている。気球に吊り下げられ空中に浮いているゴンドラ上にて，高精度の望遠鏡ポインティング制御を行うためには，制御システムを 3 段階に区切り，制御ステージごとに適切なセンサを用いて段階的にポインティング範囲を絞っていくことの有効性が論じられている。これは，問題解決のための重要な切り口である。

第 3 章では，第一段階であるゴンドラの姿勢制御および第二段階である鏡筒の方向制御について論じられている。ゴンドラの姿勢制御のためには，気球吊りひものねじれの影響をとりのぞくデカップリング制御およびコントロール・モメンタム・ジャイロによるゴンドラの姿勢静定を組み合わせた制御系が開発されている。鏡筒方向制御については，アジマスおよびエレベーションの 2 軸制御が行われている。これらを総合することにより，成層圏高度を飛行中に生じた外乱運動に対して，約 30 秒角の精度および 5Hz の応答周波数をもってポインティング制御を達成することができ，対象天体を主鏡視野内に捉えることが可能であることが示されている。これは重要な成果である。

第 4 章では，第三段階である光路のポインティング制御について論じられている。主鏡視野内に捉えられた目標天体を観測カメラ中心に固定するために，光電子倍増管(PMT)を用いた高精度位置センサとピエゾ駆動型 2 軸可動ミラー(TTM)を組み合わせた光学系を構成し，ミラー角度の制御により高精度ポインティングを実現するシステムが構築されている。惑星を観測対象とし評価試験を行った結果，アジマス方向 0.2 秒角，エレベーション方向 0.1 秒角のポインティング精度を，約 60Hz の閉ループ周波数にて達成できたことが示されている。これは非常に重要な成果である。

第 5 章では，第 4 章で開発された高精度ポインティング制御を，MEMS 型のミラー駆動機構で実現するための評価試験について述べられている。ピエゾ型ミラー駆動機構には 100V 程度の高電圧を印加する必要があるが，このような高電圧は宇宙環境では放電の原因となってしまう。一方，MEMS 型ミラーは 10V 程度の低電圧で駆動することができ，将来，衛星搭載のポインティング制御系に応用できる可能性が高い。さらに，ジャイロの振動などの高周波擾乱の影響を取り除くためには，応答周波数がより高いことが望まれる。しかしながら，駆動部の慣性が小さい MEMS 型駆動機構に対して安定な角度制御を実現するのは容易なことではない。評価試験の結果，駆動系のダイナミクスを同定し，適切な 2 自由度制御を施すことにより，数 100Hz に至る広帯域まで安定したポインティング制御が可能であることが示されている。これは，実用性の観点から有用な成果である。

第 6 章は，結論である。

以上要するに，本論文では，成層圏高度を飛行する高層気球に吊り下げられたゴンドラに搭載された望遠鏡により理学観測を行うために，0.1 秒角の精度にせまるポインティング制御を実現するためのシステム開発を行い，地上試験およびフライト実験により，その有用性を明らかにしている。この成果は，航空宇宙工学および宇宙探査工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。